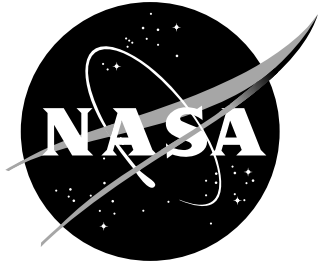# The Airframe Noise Reduction Challenge

David P. Lockard
Langley Research Center, Hampton, Virginia

Geoffrey M. Lilley
Pennsylvania State University, State College, Pennsylvania

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621–0134

- Phone the NASA STI Help Desk at (301) 621–0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076–1320

NASA/TM–2004–213013
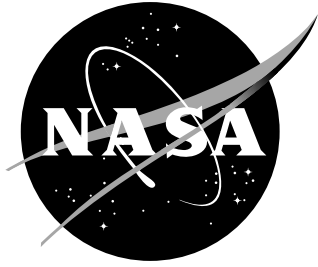
The Airframe Noise Reduction Challenge

David P. Lockard
Langley Research Center, Hampton, Virginia

Geoffrey M. Lilley
Pennsylvania State University, State College, Pennsylvania

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681–2199

April 2004

Acknowledgments

The authors would like to thank Dr. Christopher Rumsey for contributing to the generation of the NACA 4412 database.

Abstract

The NASA goal of reducing external aircraft noise by 10 dB in the near-term presents the acoustics community with an enormous challenge. This report identifies technologies with the greatest potential to reduce airframe noise. Acoustic and aerodynamic effects will be discussed, along with the likelihood of industry accepting and implementing the different technologies. We investigate the *lower bound*, defined as noise generated by an aircraft modified with a virtual retrofit capable of eliminating all noise associated with the high lift system and landing gear. However, the airframe noise of an aircraft in this "clean" configuration would only be about 8 dB quieter on approach than current civil transports. To achieve the NASA goal of 10 dB noise reduction will require that additional noise sources be addressed. Research shows that energy in the turbulent boundary layer of a wing is scattered as it crosses trailing edge. Noise generated by scattering is the dominant noise mechanism on an aircraft flying in the clean configuration. Eliminating scattering would require changes to much of the aircraft, and practical reduction devices have yet to receive serious attention. Evidence suggests that to meet NASA goals in civil aviation noise reduction, we need to employ emerging technologies and improve landing procedures; modified landing patterns and zoning restrictions could help alleviate aircraft noise in communities close to airports.

Contents

1 Introduction

The goal of 10 dB noise reduction is scientifically demanding because it means reducing the acoustic power by 90 percent. NASA's long-term goal is to reduce aircraft noise by 20 dB. In recent years, aircraft engine noise at take off and on approach has been reduced by an intensive research effort involving industry, academia, and research establishments. The greatest contributions to engine noise reduction have come from the introduction of high bypass ratio engines and successful applications of liner technology. Over twenty years ago, researchers determined that airframe noise was of secondary importance, so there has not been a commensurate reduction in airframe noise. Currently, the result of the success in engine noise reduction has meant that on the approach to landing, airframe and engine noise are comparable. Thus, any further reduction of aircraft noise on the approach can only be obtained if both engine and airframe noise are reduced by roughly equal amounts. At take off, when the engines develop maximum power, the engine remains the major source of aircraft noise. Recent theoretical and experimental studies into the physics-based sources of airframe noise have uncovered not only most of these sources, but also methods for their reduction. However, most of these methods have yet to be implemented, and the anticipated noise reduction is relatively modest in comparison with NASA goals.

This report identifies technologies with the greatest potential to reduce airframe noise. Acoustic and aerodynamic effects will be discussed, as well as the likelihood of the aircraft industry adopting the new technologies. Although the current NASA quiet aircraft technology program is not sufficiently endowed to validate or even investigate all the proposed technologies, significant progress is possible if the present research is aggressively pursued. However, it is unlikely that technology alone will meet the 10 dB goal within 10 years. An investigation of the *lower bound* for airframe noise reveals that there will still be a significant shortfall. The *lower bound* is the noise generated by an aircraft modified by a virtual retrofit capable of eliminating all noise associated with the high-lift system and landing gear. The retrofit is assumed to have no performance penalty. Once the *lower bound* has been established and calibrated in terms of the aerodynamic parameters of the aircraft, it is possible to assess how far current technology can be used to meet noise reduction goals. The somewhat discouraging result results show that the *lower bound* is within 10 dB of current aircraft noise levels on the approach. Although the *lower bound* is merely conceptual, it is developed in a scientifically rigorous manner using formulas for acoustic scattering. Current research has shown that the energy in the turbulent boundary approaching the wing trailing edge is scattered as it crosses the trailing edge. Noise generation through scattering appears to be the dominant noise mechanism on an aircraft flying at constant altitude in the clean configuration with all high-lift devices stowed. Hence, trailing-edge scattering is used as the dominant noise mechanism for the virtual aircraft used to define the lower bound. A 'dirty' aircraft is one flying in a typical approach configuration at high angle of attack with the flaps, slats, and landing gear deployed. The goal is to reduce the excess noise in the dirty configuration to those of the clean aircraft, but then trailing-edge scattering must be reduced. Eliminating scattering would require significant changes to the aircraft, and practical reduction devices have yet to receive serious attention. Present evidence suggests that to meet the NASA near-term goals in civil aircraft noise reduction, we will need to employ the currently emerging aircraft noise technology, and make progress in implementing improvements to aircraft safe landing procedures. Modified landing patterns will allow for greater separation between communities living close to the airport and the aircraft on the approach to landing. An important step in helping to alleviate community noise nuisance in areas close to airports would be to introduce further zoning restrictions. This report does not address the problem of military aircraft that also create extensive noise annoyance in those communities living close to military airfields. The design of military aircraft is less conducive to the application of noise reduction techniques at take off and landing because modifications would be at the expense of their military performance. However, communities near military airfields would have a right to demand greater separation between people and military airports once stricter zoning restrictions are put in place for commercial airfields.

Since the beginning of the jet transport age in the early 1950s, civil transport aircraft at take off and landing have produced an annoyance to populations living close to airports throughout the world. Land-use planning has in a few cases enabled new airports to be built far from the centers of population. However, soon after an airport has been built, housing developments emerge and encroach on the airport; inevitably, new residents will make claims that the noise from civil aircraft is intolerable. The control of aircraft noise in the vicinity of airports from the late 1960s to the present day has been achieved by setting statutory noise limits and monitoring the aircraft noise during every take off. Additionally, the noise of all new aircraft must meet stringent levels set by the Federal

Aviation Administration (FAA) in Federal Aviation Regulation (FAR) Part 36 and the International Civil Aviation Organization (ICAO) in Annex 16. Currently, all civil transport aircraft must meet the limits set by FAR Part 36 Stage 3, and new requirements will be introduced as a Stage 4 limit in the near future. Naturally, the concerns of the people exposed to aircraft noise are central to all noise certification, but noise limits must be carefully selected within the bounds of the available technology and the economic viability of the aircraft.

Due to the great success in noise reduction methods during the past 40 years, further noise reduction is more difficult to achieve. In the past, the engine was the main source of aircraft noise. However, the changeover from the straight-jet engine to the high-bypass ratio front-fan engine has not only greatly reduced its radiated noise, but also resulted in a reduction in the fuel burn and a consequent economic benefit to civil aviation. It is not often that a solution to noise reduction is accompanied by a gain in economic performance and cost benefit. However, noise from the airframe on the approach is only marginally lower than the engine noise. Indeed, on some modern transport aircraft, the engine noise is less than the airframe noise on the approach. Therefore, further reduction in aircraft noise can only be achieved by addressing both airframe and engine noise, which involves major reductions in the noise of all the individual sources contributing to these general classes of noise.

Research into airframe noise prediction and reduction started in the early 1970s. A large experimental data-bank was acquired from which Fink[1] produced an empirically based airframe noise prediction method. This research was reviewed by Crighton[2] who defined airframe noise as the nonpropulsive noise of an aircraft in flight, which is exemplified by the noise of a glider. However, an analysis of the available theoretical and experimental results in the 1970s showed that the peak values of airframe noise were on the order of 10 dB below those of the engine at the three checkpoints used in noise certification. These measurement points include 6500 m from the start of roll during take off, sideline at 450 m, and 2000 m from touchdown when on a 3° glide slope during approach. Current aircraft design technology, especially in regard to the design of high lift devices, renders sections of the Fink prediction method obsolete. Thus, it is no longer reliable as a prediction tool and gives little guidance to methods for noise reduction that can be applied to modern aircraft.

A noteworthy feature of airframe noise is its scaling with aircraft speed. Consider as a baseline case the noise below an aircraft in straight and level flight without flaps, slats, and landing gear. This operating condition describes a "clean" aircraft as opposed to the "dirty" condition when high-lift devices and the undercarriage are deployed. If the noise of the engine and its interference with the airframe are deducted, then for a wide range of aircraft, including gliders and birds, the noise intensity at ground level varies approximately as V^5, where V is the aircraft flight speed. The V^5 law was originally derived by Ffowcs Williams and Hall[3] and later confirmed by Howe[4]. Brooks and Hodgson[5] experimentally confirmed the formula. The theory shows that the dominant noise source on the airframe arises from the noise generated by scattering energy contained in turbulent eddies within boundary layers in the vicinity of an edge. Thus, the source of noise lies in the turbulent fluctuations in the wing boundary layers. Only fluctuations within an acoustic wavelength of the trailing edge are scattered. The spectrum of the noise ranges from 50 Hz to over 10 kHz. Aircraft size and mass determine the noise intensity at ground level.

Early work on airframe noise included a definitive study by Kroeger, Gruska, and Helvey[6] on the silent flight of the owl. The owl is the only known flying object that can fly silently within the range of frequencies above 2 kHz. The study of the owl is important in spite of the bird's small size, mass and low flight speed compared with the airplane. The owl flies at a high angle of attack similar to a landing aircraft. Furthermore, its noise sources are also related to the pseudo-turbulent pressure fluctuations in the wing boundary layers and from its legs. It should be a very noisy flying object, but it has acquired special feathers on its wings and legs, different from those on all other birds, that allow it to fly stably and quietly at a high angle of attack. The comb at the leading edge of its primary feathers acts like a row of vortex generators: it removes the leading-edge laminar separation by generating a carpet of streamwise vortices that form a quasi-turbulent, fully attached boundary layer over the entire wing upper surface. Thus, the owl's flight is silent in the range of frequencies heard by its prey. Any study of airframe noise, including methods of noise reduction, needs to address the physical principles of what can loosely be called *owl technology*. A recent review of this subject has been given by Lilley[7][8].

Although owl technology can be used to reduce the noise from scattering, different technology will be required to eliminate noise associated with the high-lift system. This paper reviews technology that can be used to reduce airframe noise and approach the NASA goal of 10 dB noise reduction. It will be shown that even if all noise from the high-lift system and landing gear are eliminated, the goal will not be met. To demonstrate the shortfall, the

paper discusses the notion of a *lower bound* to airframe noise of current commercial aircraft. The *lower bound* corresponds to the ideal situation of an aircraft flying in level flight in the clean configuration while producing high lift. In other words, this virtual aircraft can generate high lift and fly at approach speeds without suffering any extra noise from a high-lift system and undercarriage.

Noise mechanisms that are active in the clean state are influenced by the flight speed and lift on the wing. The *lower bound* corresponds to the minimum noise that an aircraft can produce when trailing edge scattering of boundary layer turbulence occurs. Unfortunately, the *lower bound* for conventional aircraft does not meet the 10 dB goal, which implies that the noise of the clean airplane must be reduced to meet the NASA goal. This may be a more difficult problem than the present focus on reducing the noise of high-lift devices. Any additional noise reduction would require owl technology to minimize scattering, but the applicability and viability of this technology to commercial aircraft has not been thoroughly studied.

The use of aircraft noise reduction technology to retrofit aircraft or modify designs is not the only technically possible and economically feasible method to attack the noise nuisance. All over the world, airports have been designed with little thought for careful community zoning to prevent aircraft noise from adversely affecting the lives of people living close to the boundary fences of the airports. Planning restrictions have generally been nonexistent, and their absence has contributed to what has become an immense problem on a global scale. Airport authorities and government agencies need to address this problem and make it a priority to move people away from the regions of excessive noise around airports. Moving people will be costly, but so are the alternatives. The combination of airport community zoning restrictions around airports plus the use of aircraft noise reduction technology will have a far greater chance of success in meeting the NASA goals than one of these methods alone.

Other alternatives need to be fully explored, including coordinating flight operations with new community zoning restrictions. An investigation among civil aircraft pilots should be made to ascertain if aircraft on the approach can provide greater separation to the population while still following current safe landing procedures. One possible method is for pilots to use only part of the runway length for landing. Current practice is for pilots to lower the undercarriage early, and to fly low over the remaining houses while getting the airplane into its final landing attitude before touchdown. The actual landing currently occurs at the first or outer marker, and is quickly followed by deployment of the thrust reverser and speed brakes. The deceleration of the aircraft to taxiing speed is completed in less than half the length of runway, and the aircraft turns onto the taxiway to the terminal buildings. If the landing point were moved to one-third the way down the runway, greater separation with the population could be achieved. The pilot could make adjustments and use the entire runway in an emergency, but the pilots must make a determination of whether such an approach is completely safe.

More advantageous approach and landing flight trajectories would require modifying current landing regulations. One possibility is to fly the aircraft on a continuous descent path, as described by Smith[9], joining the Instrument Landing System (ILS) glide slope of $3°$ while still at high speed. The aircraft could maintain a minimum drag and power configuration for as long as possible. Full flaps, wheels down and high thrust should only be applied in the final phase of the approach to touchdown. Furthermore, the location of undercarriage deployment could be set beyond the nearest communities to the airport. This approach and landing trajectory would provide an important noise reduction for all people living under and to the side of the flight path of 5-10 Effective Perceived Noise Level (EPNL) dB at 4 km from the airport. The aircraft height would be increased to about 200 m at this location.

In the next section we explain some of the terminology used in the paper. Then, a practical example is used to demonstrate the requirement to reduce all important component noise sources commensurately to achieve significant overall noise reduction. A discussion of technology that could be used to reduce airframe noise follows. The difficulty in achieving the 10 dB goal is then demonstrated through an analysis of the *lower bound* of airframe noise. The paper concludes with some recommendations for reducing community noise.

2 Definitions

Airframe noise is the total aircraft noise minus the noise from the engine and noise from engine/airframe interference. In this paper, we divide airframe noise into the following categories:

1. Wings including tail surfaces and fuselage

2. <u>High Lift Devices</u> including trailing-edge flaps, leading-edge slats, and brackets

3. <u>Undercarriage</u> including main and nose wheels, axles, oleo legs and struts, fairings, brake cables and hydraulic pipes, wheel wells, and doors.

Airframe Noise is defined in terms of the noise intensity, $I(Watts/m^2)$, as measured by an observer at ground level directly below the aircraft when $\theta = 90°$. The angle θ is measured in the longitudinal flight plane from downstream. This is not necessarily the location of maximum noise, which in some cases occurs between $80 - 100°$. Because the human response to sound varies greatly with frequency, the intensity is usually calculated within frequency bands. To simplify the analysis, we use a single measure of the noise: the overall sound pressure level (OASPL). The OASPL is measured in units of dB as

$$\text{OASPL} = 10 \log_{10} \frac{I(\text{Watts/m}^2)}{I_{\text{ref}}} = 120 + 10 \log_{10} I(\text{Watts/m}^2) \tag{1}$$

where $I_{\text{ref}} = 10^{-12}$ (Watts/m^2) and $I = <p^2>/\rho_\infty c_\infty$. Airframe noise is highest on the approach to landing when the high-lift devices are operational and the undercarriage is down.

As required under noise certification, the typical flight speed on the approach is 1.3 times the aircraft stalling speed with the aircraft at its all-up-weight. Typically, the flyover speed will be taken as 132 kt = 68 m/s with the aircraft flying at an altitude of 120 m. This condition occurs about 2 to 3 minutes before landing. Thus, for an aircraft having a maximum wing loading of 4500 N/m^2, the overall lift coefficient based on wing area is $\bar{C}_L = 1.59$ with $C_{L\text{max}} = 2.69$. The analysis must be modified appropriately to account for the wide variability in flight speed, height, and weight. It is important to note that a change in approach speed from 132-145 kt results in an increase in OASPL of 2 dB. Similarly, a change in height from 120 to 150 m leads to a decrease in OASPL of 2 dB.

3   Effect of Component Noise Reduction

The primary components generating airframe noise are flaps, slats, and landing gear. In general all three components have similar amplitudes, but their peaks occur at different frequencies. If we have three spectra of nearly equal amplitude, then to reduce airframe noise by 4 dB means all three components must have their component noises reduced by 4 dB. Table 1 shows the effect of reducing the noise of three sources separately and simultaneously. The table gives the sound pressure level (SPL) of three distinct sources in units of decibels. The combined effect of all the sources is given by the overall sound pressure level, which is calculated by logarithmically adding the separate noise from each component. This method is usually oversimplistic because there will always be flow interference effects between the components. The interference produces additional noise that must be accounted for separately. Nonetheless, the simplified analysis shown in table 1 clearly demonstrates the need to reduce all noise sources by commensurate levels to achieve any significant overall noise suppression. For modern aircraft, engine noise on the approach is around the same intensity as airframe noise. Therefore, four major noise sources must be reduced on approach. Furthermore, distributed noise sources such as trailing-edge scattering over the wings and other secondary noise sources are likely to become important with only modest reductions in the four primary noise sources.

4   Technology to Reduce or Eliminate Airframe Noise

Flaps, leading-edge devices, and landing gear are the three main components of airframe noise. The first step in achieving significant airframe noise reduction must be to eliminate the loudest noise sources. In this section,

Table 1: Estimates of the effect of reducing noise sources individually and simultaneously.

	Case (a)	Case (b)	Case (c)	Case (d)
Source i	SPL (dB)	SPL (dB)	SPL dB	SPL (dB)
1	80	70	0	76
2	80	80	80	76
3	80	80	80	76
$OASPL$	84.78	84.62	83.0	80.79

we investigate technology that could be applied to the airframe to reduce or eliminate airframe noise. We present concepts and devices that could be applied to existing aircraft to reduce airframe noise in the near term, along with some novel approaches that could be incorporated into new aircraft designs. We also consider flight operations that could further reduce the noise impact on communities near airports.

4.1 Flaps

The major noise source from flaps occurs at the side edge where a strong vortex is formed because of the sharp change in lift between the flapped and unflapped portion of the wing. The continuous moldline link (CML) has been shown experimentally to drastically reduce the noise from the flap edge. Computational studies have shown that the vortex system is more diffuse and rolls up further downstream as seen in figure 1. A similar effect can be realized through the use of a porous flap tip. The section of the end of the flap that needs to be porous is only a small percentage of the chord. If the correct impedance is used, the pressure and suction surfaces are allowed to communicate in a fashion that smooths out the transition from the solid flap to the unflapped region. This process also tends to diffuse the tip vortex.

Some disruption of the flap vortex system can also be obtained through the use of a fence. A fence is similar to a winglet in that it moves the vortex generated by the discontinuity in lift away from the tip. This change results in less noise and has a potential aerodynamic benefit of decreasing the induced drag on the flap. Fences are more problematic for practical applications because they use a rigid surface to stop all spanwise flow and are susceptible to separation. Furthermore, they have a drag penalty during cruise.

Microtabs have also been found to be effective in decreasing flap noise. These thin strips of rectangular cutouts can be placed near edges to thicken shear layers thereby affecting the stability characteristics. Modest improvements over a wide frequency range have been observed, and the tabs can be used to eliminate tones. Side-edge blowing also had the potential to move and diffuse the vortex system.

4.2 Leading-Edge Devices

Noise reduction technology for leading-edge devices such as slats is less advanced than for flaps, but several approaches appear promising. It is still uncertain whether the loud, high frequency noise source observed in model experiments and computations is a scale phenomena, but the mechanism is now better understood, so it can be eliminated. Vortex shedding from the trailing edge of a slat occurs at a high amplitude when the ratio of the boundary layer thickness to the trailing-edge thickness is within a certain range. However, the intense source is caused by resonances between the shedding mechanism and the gap between the trailing edge of the slat and the leading edge of the main element. Geometrical relations that would result in reinforcement of this noise source need to be carefully avoided during all phases of flight operations. Thinning the trailing edge has been shown to be effective in eliminating the noise from leading-edge devices. Changing the boundary layer thickness with vortex generators or some other form of flow control should also be effective. Trailing-edge notches have also minimized this noise mechanism. The other major noise source for leading-edge devices is believed to be instabilities in the shear layer in the cove region, including unsteadiness in the recirculation zone and reattachment point. Porous slat pressure surfaces that would allow communication between the different regions on the slat should be an effective means of reducing the unsteadiness in the cove and significantly affect the noise. Another approach is to fill the
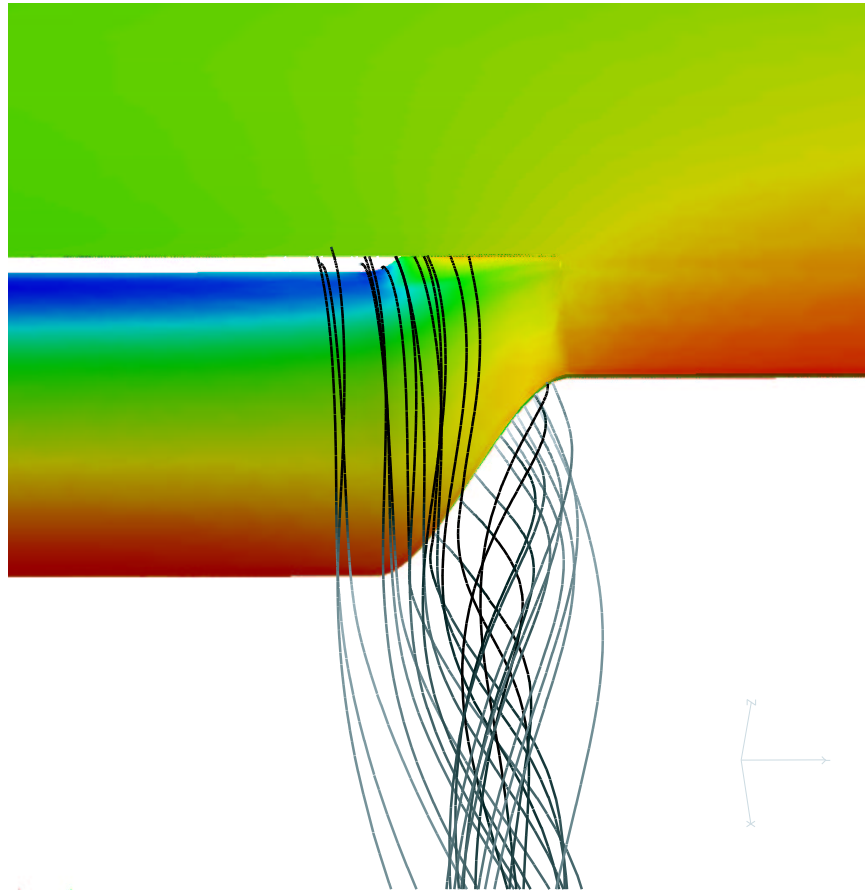
Figure 1: Streamlines and pressure contours around a continuous moldline link

cove region. Some experiments have already been performed with solid inserts designed to follow the isobars in the cove. The insert, commonly called a filler, eliminates the strong shear layer that develops at the first edge of a standard slat. As long as the filler is designed properly, the flow remains attached, and the noise generation mechanism is greatly reduced. Some additional noise near the wing tip has been observed when a filler is present, thus, this method needs further investigation. For real applications on planes, the filler would have to be made so that the slat could be stowed. New advances flexible materials may make this a practical solution.

4.3   Wing Morphing

Currently, wing morphing is receiving considerable attention because of the aerodynamic advantages of being able to dynamically change the shape of a wing based on the flight regime, but it would also have a desirable side effect on the noise because the slats and flaps could be eliminated. Morphing could be performed by using smart materials that have preferred states dependent on the temperature or electrical current in the metal. Shape-memory alloys can be taught to remember any useful shape, then molded into a new shape. They will return to their original shape when exposed to enough heat. Piezoelectrics act in a similar fashion with electric current providing the trigger instead of heat. If these materials were embedded in a wing, a pilot could morph the wing from a cruise configuration to a high-lift configuration by applying heat or electricity. Because the wing itself is forced to deform, no sharp edges, corners, or gaps would be produced. Hence, the noise characteristics should be the same as that of a clean airplane. However, significant technological challenges need to be addressed to make morphing airplanes a reality. The amount of heat or electricity that must be applied to achieve the desired deformation is often excessive. There is also the material problem of finding metals for the wing that can be

stretched and compressed into the appropriate shapes without breaking. All of the materials must also be resistant to fatigue from being cycled through the different configurations. Furthermore, it is debatable whether a wing can be deformed enough to produce lift similar to a multielement configuration, especially for a large commercial transport. Nonetheless, wing morphing has shown great promise and may eventually allow planes to be designed without flaps and slats.

A passive form of wing morphing has already been investigated for its noise benefits for flaps. Experiments and computations have shown that the side-edge vortex generated at a flap edge can be drastically diffused by providing a smooth transition from the end of the flap to the trailing edge of the wing. Continuous moldline technology (CMT) is already in use as a means to construct flexible structures, and has been proposed for making the flap edge transition region, termed a continuous moldline link (CML). This problem is much simpler than morphing the entire plane because the system does not need to generate the forces causing the deformation-it only needs to respond properly to an externally applied force. Also, the CML is relatively small and is not a major load-bearing component. To design a CML that can maintain the proper shape under aerodynamic load is still a technological challenge, but the likelihood of near-term success is good. The expected flap noise reduction in EPNL for a large quad with a CML is over 5 dB based on the estimates of Rackl et al.[10]. All of the other noise sources must be decreased commensurately to achieve this reduction. Although a flap with a CML still has an additional trailing edge and brackets, the noise is not very different from that of a wing without a flap.

4.4   Circulation Control

Circulation control is a means to eliminate both the flaps and the slats. One form of circulation control is the jet-flap, where a stream of air emanating from near the trailing edge of a wing is used to simulate the effects of a flap. An alternative is to use additional engines during takeoff and landing to provide the additional lift needed during these phases of flight. Many early researchers conjectured that the ultimate solution would be vertical takeoff with a vertical thrust greater than the all-up weight of the airplane. Kucheman, Maskell, and Lilley patented such a design in the 1950s. Also in the 1950s, A. A. Griffith invented the vertical takeoff aircraft that employed multiple lift engines that were closed down during the cruise. Both these schemes were proved technically feasible but uneconomical. In the military application, the Harrier proved effective as a short takeoff, vertical landing (STOVL) aircraft, but its commercial counterpart was criticized for its fuel burn. Even when operated from the center of an airfield, takeoff and landing of these vehicles would be very noisy.

The growing field of aeroacoustics seems to be the future path of noise reduction. This field requires the combined expertise of aerodynamicists and acousticians, Currently, there is a great emphasis on circulation control in the aerodynamics community which may lead to revolutionary changes in high-lift systems, but the new technology needs to be evaluated from an aeroacoustic perspective. Powered lift, including the use of the jet flap, would enable high-lift coefficients to be achieved without the need for mechanical flaps and slats. Furthermore, such short takeoff and landing (STOL) aircraft are desirable because they would have much shorter ground rolls resulting in touch down and lift off points that are farther from the surrounding population. Despite the potentially enormous acoustic benefit that could result from circulation control, very little is known about the noise characteristics of the devices that would be used to achieve such control.

Many forms of circulation control are currently being researched, and some previously abandoned schemes may be rejuvenated by active control. Unsteady suction and blowing appears to have many possible applications for control on commercial aircraft. However, many of these schemes are likely to generate excessive noise in the process of controlling the flow. Hence, it is imperative that the aerodynamicist and the acoustician work synergistically to create flow control methods that are also quiet.

4.5   Landing Gear

When considering airframe noise reduction, it is crucial to reduce gear noise, as well as the wheel-well cavity noise when the undercarriage is down. The latter is mainly tonal, and schemes have been suggested to eliminate this tonal component. Most of the remainder of the noise from landing gear is a result of bluff body separation and shedding from the various components. Because the size of the components varies greatly, the noise spectrum is broadband. However, the peak in the spectrum appears to be fairly low (around a few hundred hertz). Removal

of the small parts such as hydraulic lines and nuts has been shown to reduce the high frequency noise by several decibels. Although actual removal of the small parts would be impractical, some of the small components could be hidden behind larger ones in relatively dead zones of the flow. Some small components could also be enclosed by the larger ones.

A rigid fairing could be placed around the landing gear to present the oncoming flow with a more aerodynamic shape that would not be subject to strong shedding. The advantage of a fairing over the entire gear is that it would reduce the noise over the entire spectrum, including the low frequency region of the peak. Nonetheless, the undercarriage itself is considered optimal design, and it is unlikely that significant modifications or external fairings will be permitted because they make maintenance and inspection difficult. A compromise that may still be of some benefit is partial fairings. The door itself could be modified to provide some shielding of the other components, and other fairings could be designed to swing down into place independent of the gear. This design would allow them to move away from the gear for ease of inspection, but would add to the complexity of the system. Other deployable fairings are under investigation.

Virtual fluidic fairings could provide a similar noise benefit without interfering with maintenance. By blowing air out of the landing gear, the streamlines from the oncoming flow would be diverted around the gear, thereby eliminating the shedding. The difficulty is that the gear has a large frontal area and the wheel bogey is often several feet long. The air flow rate would be approximately the frontal area times the speed of the oncoming flow. At Mach 0.2, it is unlikely that so much air could be bled from the engines at idle, and a great deal of tubing would be required to direct the blown air properly. However, proper design could minimize the air requirement. Furthermore, localized blowing may prove sufficient to eliminate vortex shedding.

A spike placed forward of a bluff body at transonic, supersonic, and hypersonic speeds can reduce drag, and this has been suggested as a means to modify the flow field around a landing gear. However, it seems unlikely that a forward spike could be effective at low speeds. Preliminary tests would be needed to explore the potential of the long slender spike with and without forward blowing from its apex. The spike would need to be retracted just before touchdown. Even if such a scheme was found to be satisfactory for noise reduction on a single wheel, it is doubtful that it would retain its effectiveness over the second and third set of wheels in a six-wheel undercarriage bogey.

It has been suggested that the landing gear could be eliminated, but the alternative strategies for landing large, commercial aircraft are currently in the realm of science fiction. Some alternatives include blowing air out of the runway to provide a cushion of air or magnetic levitation. Implementations of these systems would require enormous capital investments at airports and would have major safety issues. At the moment, other means of noise reduction appear more economical, but future breakthroughs may change the situation. A system study by J. Russell (private communication, 2002) showed that eliminating gear noise alone from generic aircraft would produce a minimal EPNL noise reduction. However, this view does not conform with flyover measurements of current aircraft that indicate gear noise is a major, and possibly dominant source.

4.6   Other Noise Reduction Alternatives

Although present noise reduction technology may allow airframe noise to be reduced substantially, it is doubtful that enough technological advances will occur over the next few years to meet NASA's goal of reducing airframe and engine noise by 10 dB. Thus, alternative methods such as flight operations must be investigated. The current $3°$ instrument landing system (ILS) glide slope and early deployment of the landing gear is primarily responsible for the noise nuisance experienced by people living under the approach path at airports. Present landing procedures require the aircraft to fly at a speed around 68 m/s at an altitude less than 300 m upon approach. The altitude is reduced further to 120 m when 2 km from touchdown. The landing gear is lowered when the plane is 6 km from landing, which corresponds to 2-3 minutes of flight time. A number of proposals for increasing the separation between landing aircraft and residents living near airports are summarized by Smith et al.[9]. Of course, safety in the air is paramount, and the present air traffic control procedure employing the $3°$ glide slope could only be changed if it were demonstrated that alternate strategies were as safe as those in use today.

We must be careful when predicting the effects of changing the flight path and speed on approach noise, but the global effect can be estimated by making some approximations. When the primary noise source involves scattering, $p'^2 \propto V^5$. For spherical wave propagation, $p'^2 \propto 1/r^2$. Combining the effects, the additional noise

reduction from operations can be estimated as

$$\text{Noise Reduction} = 10 \log_{10} \left(\frac{V}{V_{ref}} \right)^5 \left(\frac{r_{ref}}{r} \right)^2 \tag{2}$$

The distance from the plane to the observer is r, and V is the speed of the aircraft. The reference quantities denoted by ref are the values for a normal approach. The noise from a plane flying 10 percent higher and 10 percent slower during landing would achieve an additional noise reduction of 3.1 dB. Because the certification points are so close to the touchdown location, it may be difficult to change the flight operations sufficiently to alter the noise levels at these points. However, the footprint of the noise during approach is much more important in determining the total community impact from landing aircraft. The overall footprint of unacceptable noise levels can be altered significantly by changing the flight operations, which will help meet the goal of 10 dB of noise reduction.

Equation (2) shows that the change in speed has the greater influence on the overall noise levels. However, the scaling law with velocity may be slightly different for the engines. Therefore, keeping the plane away from the observers may be more important to reduce the overall noise. Assuming no change in the noise from speed, it would take a 45 percent increase in the altitude to achieve 3.2 dB of noise reduction. Some studies should be performed to determine the trade-off between distance and velocity so that an optimal flight path could be developed. It is possible that current aircraft cannot fly the preferred flight schedule, but simple modifications to the planes, such as speed brakes, would greatly increase their flight envelopes.

4.7   Noise Prediction

An important aspect of all discussions on airframe noise reduction is the need to develop methods by which airframe noise can be predicted both accurately and rapidly. This is a challenge equally as important as finding methods to reduce noise. Future aircraft will be designed to meet both performance and noise certification goals. The designer urgently needs the tools to predict noise for different airframe and engine layouts.

Some of the concepts for eliminating the high-lift systems may prove useful in other fields upon further investigation. Aeroacoustic methods of noise control involve modifications to the unsteady flow and are often applicable to a wide range of flow problems. Thus, the methods used to minimize or eliminate high-lift noise may be suitable to reduce the noise of other sources on an airplane. However, the general applicability of the methods may not be apparent until they are investigated specifically for different sources. Our discussion has focused on ways to eliminate the high-lift system, but methods that do not appear promising for this task may prove important for other sources. Although completely eliminating the high-lift systems may not be possible within the 10-year time limit of the 10-dB noise reduction goal, this case provides a *lower bound* for the noise of an aircraft flying in a clean configuration. In the next section, we investigate the *lower bound* of airframe noise, where the dominant noise source is trailing-edge scattering.

5   *Lower Bound* Of Airframe Noise

Consider the ideal case where all high-lift noise has been eliminated leaving an aircraft in the clean condition. Furthermore, assume that the plane can fly in this clean condition while maintaining the same lift and speed as a landing aircraft. Such a virtual aircraft was investigated by Lilley[8] who showed that the plane's dominant noise source was scattering at the trailing edge. We define the *lower bound* of airframe noise as the noise that would be generated by this virtual aircraft when flying at approach conditions. Although such an aircraft is hypothetical today, the goal of our current research is to make it a reality. Hence, the *lower bound* can also be thought of as an estimate of how much noise will be generated on the next generation of planes if all of our research into eliminating flap, slat, and landing gear noise is completely successful. If we are able to reduce the noise of the high-lift system to that of the clean aircraft, but fail to meet the 10 year goal, research must be reordered to attack the more challenging problem of noise reduction of an aircraft flying in a clean condition. Furthermore, modifications must not interfere the aircraft's ability to fly in the clean condition while generating high lift.

We assume that such a high-lift hush kit does not degrade the aerodynamic performance in the approach to landing. If modifications resulted in a weight penalty for this aircraft, this would automatically be taken care of

by using the new weight throughout the calculations. The method used to estimate the *lower bound* is based on the work of Ffowcs Williams and Hall[3] on the noise scattered at the edge of a half-plane. In the next section we will review this work and consider how we can estimate the noise of the clean airplane flying at a nominal $\bar{C}_L = 0.5$.

5.1   Half-Plane Problem

The noise from turbulent boundary layer pressure fluctuations in a low Mach number flow over an infinite plane surface was shown by Powell[11] to be quadrupole and, therefore, proportional to V_∞^8, where, V denotes the freestream velocity. The analysis shows that the normal force fluctuations on the surface, which are dipole, are exactly canceled by image dipoles. Hence, the infinite plane does not augment the noise radiated by turbulent eddies in the boundary layer. However, the situation is quite different for finite surfaces. A turbulent source above a compact wing will radiate as a dipole and be proportional to V_∞^6. The wing appears compact to the source when its dimensions are small compared with the wavelength of the disturbance. However, when the wing chord is large compared with the wavelength, the acceleration of the turbulent flow as it approaches and recedes from the trailing edge causes some of the kinetic energy to be scattered into sound. The far-field radiated noise is increased from a proportionality of V_∞^6 to V_∞^5 for a sharp trailing edge. The exponent was shown by Crighton[12] to be a function of the trailing edge geometry. Crighton[2] also showed that much more noise is generated by trailing edge scattering than by any other mechanism involving eddies in the boundary layer even though the wing area can be very large.

To investigate these findings in more detail, we now consider the noise radiated from the unsteady flow past a semi-infinite plate of zero thickness and at zero incidence. The analysis will use Lighthill's acoustic analogy. This approach was first employed for the scattering problem by Ffowcs Williams and Hall[3]. They found the solution to the far-field noise problem was dominated by the singularity in the Green's function at the sharp trailing edge, analogous to the scattering of electromagnetic waves past the edge of a half-plane. In the acoustic case at low Mach number, the sources within an acoustic wavelength of the trailing edge emit noise that scatters at the trailing edge, and the intensity of the radiated noise is proportional to $V_\infty^5 \sin^2(\theta/2)$, where V_∞ is the freestream or flight velocity. The angle θ is measured from the downstream direction. We find that for level flight at height H when $\theta = \pm 90°$, the far-field noise intensity per unit volume of acoustic sources is

$$I(Watts/m^2) = \frac{c_\infty^3}{\rho_\infty} \frac{\omega_0}{2\pi^3 H^2} \frac{\rho_0^2 u_0^4}{c_\infty^5} \tag{3}$$

which is a form of the Ffowcs Williams-Hall equation given by Goldstein[13]. It is also similar to that given by Howe[4, 14] and Crighton[2, 15]. In this approximate form of the equation the space-retarded time covariance of the Lighthill stress tensor is nondimensionalized and given the approximate value of unity. The characteristic source frequency ω_0 is given by the Strouhal relation for turbulent flow $\omega_0 \ell_0 / u_0 \approx 1.7$. The characteristic length and velocity scale for the turbulence are ℓ_0 and u_0, respectively. The noise from the half-plane is an idealized problem, but it provides a good approximation to the noise of a clean aircraft. When equation (3) is integrated over the wing span, the resultant noise estimate is in reasonable agreement with experimental results. Equation (3) is for low Mach numbers and omits the Doppler factors that would be required at higher Mach numbers and directivity angles other than $90°$. Because the equivalent sources in the wing boundary layer are in motion relative to the wing, they appear to be moving very slowly to an observer on the ground. The relative velocity between the sources and the observer determines the amplitude of the Doppler factors. Because the relative velocity is small, the Doppler factors can be neglected. A $\cos^3 \beta$ term that is important for highly swept edges is also ignored. The angle β measures the sweep of the trailing edge. Howe[16] suggested that a serrated trailing edge would reduce the radiated noise by changing the sweep angle, and recent experiments have confirmed this result. However, conventional aircraft have a sweep angle of zero at trailing edges.

Computations and experiments have confirmed the relevance of the results for the half-plane to more realistic problems involving wings. Simulations of turbulence crossing a wing trailing edge have been performed by Singer et al.[17], where the radiated noise has been evaluated from a time-accurate flow solver coupled to the Lighthill acoustic analogy in the form presented by Ffowcs Williams and Hawkings[18]. Agreement was obtained with the formulation given in equation (3). In addition, measurements of trailing edge scattering noise has been measured

by Brooks and Hodgson[5] and more recently by Ostertag et al.[19], confirming the result given in equation (3) for the two dimensional airfoil.

5.2   Noise From Clean Aircraft

In the early work on the airframe noise of the clean aircraft, experiments seemed to indicate that the noise was independent of the aircraft lift coefficient. However, the present more detailed study shows that the clean aircraft noise is a strong function of lift coefficient when the aircraft $\bar{C}_L$ exceeds about $\bar{C}_L = 0.5$. This increase arises from the change in the turbulent boundary layer characteristics along the wing upper surface and approaching the wing trailing edge with increases in lift coefficient. As $\bar{C}_L$ increases, the turbulent pressure fluctuations and the turbulent kinetic energy in the upper surface adverse pressure gradient also increase. A preliminary study of the changes in amplitude and length scale of turbulence in a boundary layer was performed by using steady, two-dimensional RANS calculations of a NACA 4412. A range of incidence from zero to stall has given us some insight about the influence of the lift coefficient on airframe noise. We have also observed a reduction in airframe noise due to the large decrease in flight speed from cruise to the approach to landing. The study has used the available published results of flight tests on the clean aircraft. The amount of good data is sparse: repeated flight tests differ by more than 2 dB. To assist industry in meeting the new goals, additional accuracy could be achieved by calibrating the noise measured levels of the clean aircraft with the *lower bound*. This calibration could be obtained from RANS calculations on the complete aircraft, wind tunnel tests on complete configurations, or further "piggyback" tests as part of conventional noise certification flight tests.

For a clean aircraft with a large aspect ratio wing, we assume that its primary noise source is the scattering of noise from the wing trailing edge. For aircraft flying at lift coefficients greater than $\bar{C}_L = 0.5$, the noise sources in the upper surface boundary layer are much stronger. Hence, the noise from the lower surface boundary layer may be neglected. A good first approximation is to assume that the amplitude of the acoustic sources is proportional to the maximum turbulent kinetic energy, and the length scale of the acoustic sources equals its distance from the wall. The wall distance is of the same order as the turbulent boundary displacement thickness. At large values of $\bar{C}_L$ the maximum value of the turbulent kinetic energy occurs at distances from the wall that increase with increases in lift coefficient. We find in regions of adverse pressure gradient that y_m/δ is typically between 0.2 and 0.3, but it can be as large as 0.5. The position of maximum turbulent kinetic energy is denoted by y_m, and δ is the boundary layer thickness. The turbulent kinetic energy is $k_m = 3u_0^2/2$, and $\ell_0 = y_m$, where u_0 and ℓ_0 are the characteristic velocity and length scale of the turbulence in the upper surface boundary layer, respectively. It is further assumed that for the clean aircraft that these quantities do not vary along the wing span. Thus, to apply equation (3) to the complete clean aircraft, we must validate it against measured data found for the complete aircraft using steady RANS, wind tunnel measurements, or flight tests. Our preliminary results suggest that this method gives results for the OASPL of the clean aircraft that agree with experiments for the pre-1980 aircraft without modifying the numerical constants in equation (3). However, on modern commercial aircraft with advanced wing design and twin wing mounted engines, the average turbulent kinetic energy in the boundary layer at the trailing edge is lower than for aircraft of the pre-1980 era. Simplified calculations suggest that for the cleaner post-1980 aircraft, u_0 needs to be replaced by eu_0, where $e \approx 0.9$.

The radiated noise from the wing of an aircraft flying straight and level in the clean configuration for $\bar{C}_L < 0.5$ is found from integration of equation (3) over the span b of a wing of mean chord $\bar{c}$. The characteristic length scale of the turbulence in the proximity of the wing trailing edge ℓ_0 can be equated to the boundary layer displacement thickness $(\delta_1)_{\text{TE}}$. In the far-field at a distance H from the aircraft, in which the noise sources are considered as existing only over the upper surface of the wing,

$$I(Watts/m^2) = \frac{1.7}{2\pi^3} \frac{\rho_\infty S V_\infty^3 M_\infty^2}{H^2} \left(\left(\frac{u_0}{V_\infty} \right)^5 \frac{\delta}{\delta_1} \right)_{\text{TE}}. \tag{4}$$

The wing area is $S = b\bar{c}$, and δ_{TE} is the boundary layer thickness at the wing trailing edge. This dimensionally correct formula ignores the finite spanwise correlation length of the space-retarded time covariance. Deriving this expression from equation (3) involves an integration in the chordwise direction over all disturbances within an acoustic wavelength of the trailing edge. We must include all frequencies in the broadband spectrum, and the frequency of the peak in the spectrum is in the lower band of frequencies. Therefore, the required range of

integration is a major fraction of the chord and can be approximated by the chord itself. Clearly, this estimate is more valid for smaller aircraft and aircraft having a large wing aspect ratio. In earlier work an attempt was made to include only part of the wing chord. However, a more detailed study of the experimental data obtained from flyover tests in the 1970s showed such good correlation based on wing area alone that it was assumed integration over the mean chord was justified.[*] Here we ignore the presence of the engines and the fuselage as well as the noise from the tail surfaces.[†]

For an aircraft of all-up weight W, flying straight and level before the approach, the aircraft speed and lift coefficient $\bar{C}_L$ are related by

$$W = (1/2)\rho_\infty V_\infty^2 S \bar{C}_L \tag{5}$$

From equations 4 and 5 we find for the radiated far-field noise

$$I(Watts/m^2) = \frac{13.6}{\pi^3} V_\infty M_\infty^2 \left(\frac{u_0}{V_\infty}\right)^5 \frac{W}{\bar{C}_L H^2} \tag{6}$$

We assume that $(\delta/\delta_1)_{TE} \approx 8$, which is appropriate for a typical civil aircraft flying at high Reynolds number. Furthermore, we assume that only the wing upper surface boundary layer contributes to the far-field radiated airframe noise. If we define $F(Watts/m^2) = W V M^2/(H^2 \bar{C}_L)$, we see that the noise intensity $I \sim F$. From equations (3) and (4), the definition of F can also be written as $F = (\rho_\infty/2c_\infty^2)(S/H^2)V_\infty^2$. We prefer the former definition because it emphasizes the importance of both the lift coefficient and flight speed for a given aircraft all-up weight by noting $\bar{C}_L V_\infty^2 = (2/\rho_\infty)(W/S)$. A still further equivalent form for F is

$$F = (W/T_{th})(\rho_\infty/(2c_\infty^2)(S/h^2)V_\infty^2)/(\bar{C}_L/\bar{C}_D) \tag{7}$$

which shows the relation between F and the main aerodynamic parameters. Here, T_{th} is the engine thrust corresponding to the flight speed V, and $W/T_{th} = \bar{C}_L/\bar{C}_D$ in level flight. All these interrelationships are required in defining the noise of an aircraft during the approach.

On substituting suitable values for the typical turbulent intensity we find

$$I(Watts/m^2) = K \left(\frac{W V_\infty M_\infty^2}{\bar{C}_L H^2}\right) \tag{8}$$

where $K \approx 5.6 \times 10^{-7}$. Although the coefficient K will vary with the Reynolds number of the aircraft, we find this simple formula fits remarkably well with the experimental data collected from ground noise measurements over the past 25 years for aircraft ranging from gliders to jumbo jets.[‡] At constant height and speed and an average flight $\bar{C}_L = 0.5$, the far-field noise intensity is only a function of aircraft all-up weight. For other angles in the longitudinal flight plane, we find the noise directivity follows the $\sin^2(\theta/2)$ law. This law fits the measured data for aircraft flying straight and level in the clean state over a weight range from about 10 N to 4×10^6 N. As an example, when $W = 2 \times 10^6$ N, $\bar{C}_L = 0.5$, $V_\infty = 125$ m/s, $H = 120$ m, we find $I = 95.4$ dB, which is typical of the airframe noise from a "large quad" such as the $B747 - 100$.[§]

The spectrum of noise is important, for without it we cannot calculate the high frequency weighting required for calculations involving perceived noise levels. In this simplified formulation, we will find only a measure of the peak in the frequency spectrum for the complete clean aircraft. If we define the Strouhal number for the frequency of the peak in the spectral density as

$$S_T = \frac{f_{peak}\bar{c}}{V_\infty} = \frac{1.7}{2\pi} \frac{u_0}{V_\infty} \frac{\bar{c}}{\delta_{TE}} \left(\frac{\delta}{\delta_1}\right)_{TE} \tag{9}$$

---

[*]Clearly, this was a gross approximation and applied only to that data set. We will discuss later the reasons why we may need to amend this assumption when dealing with the modern commercial aircraft fleets.

[†]Corrections for these components can easily be made by summing just those contributions that include a near horizontal scattering trailing edge.

[‡]The value of K quoted above is more appropriate for aircraft of the pre-1980 era than to more modern commercial fleets.

[§]For later versions of the B747 with a new wing of greater aspect ratio, a smaller value of K is more appropriate.

and use the values of $u_0/V_\infty = 0.066$, $(\delta_1)_{TE}/\bar{c} = 0.0044$, and $\delta/\delta_1 \approx 8$, we find that $S_T \approx 4$. As an example for a large civil transport with a mean chord of $\bar{c} = 7$ m flying at a speed of $V_\infty = 130$ m/s, we find $f_{peak} = 78$ Hz.¶

The decay law for the spectrum beyond its peak is not universal and is a function of aircraft geometry. In addition the spectrum has a broad peak before the decay occurs. As is the case for many shear layers, the frequency spectrum beyond the broad peak falls as f^{-n} where $n = 1.5$ to 2.

It is assumed that this clean aircraft has a broadband spectrum with all tones suppressed. The noise at $\bar{C}_L = 0.5$ with flaps, slats, and undercarriage stowed can be determined from flight tests, but the results are sparse and not well documented for modern aircraft. In addition, the measurements of aircraft noise at ground level need to be corrected for engine noise and engine-airframe interference to obtain the true airframe noise component. It is only by this method that we can find the true clean aircraft OASPL and its spectral density.

5.3 Clean Aircraft at High Lift
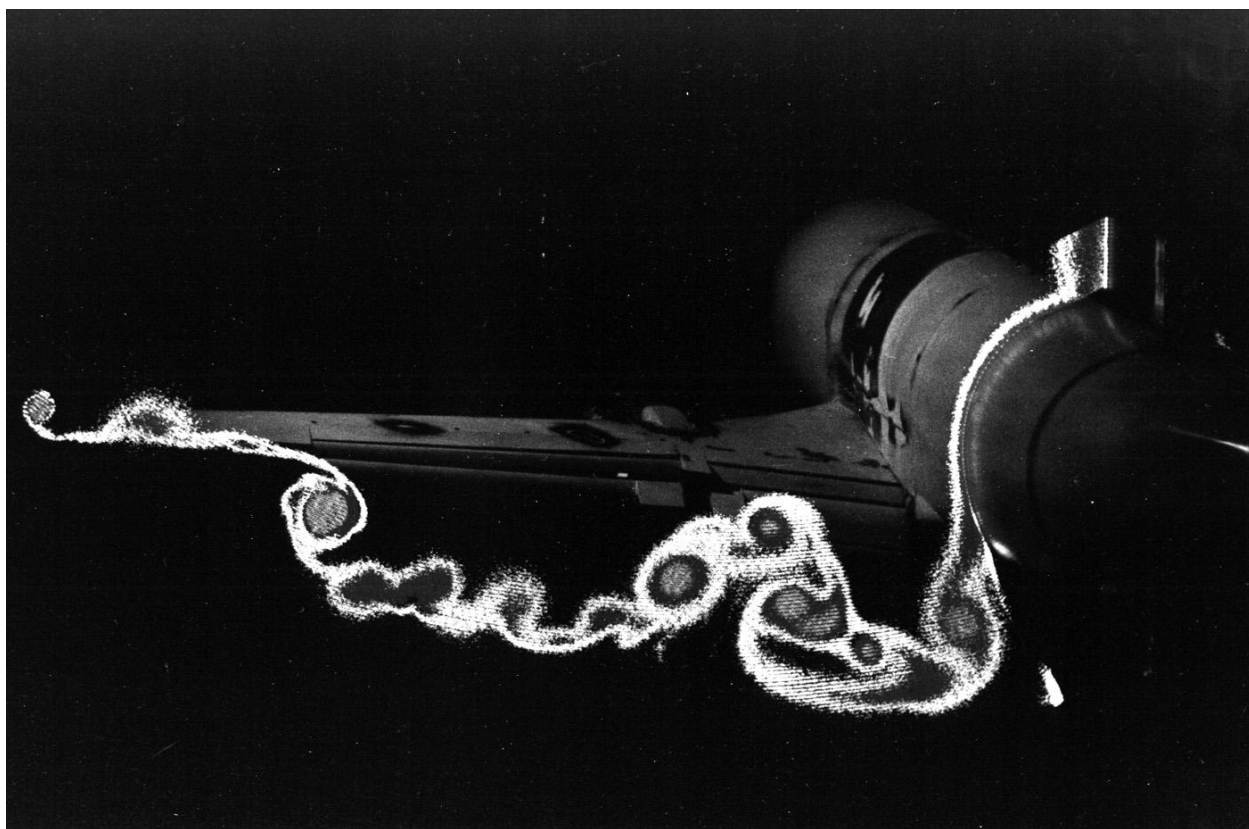
Figure 2: The structure of the wake downstream of high-lift extended flaps. (Photograph courtesy of J. P. Crowder[20])

For an aircraft on the approach with part-span Fowler flaps deployed and the aircraft $\bar{C}_L = 1.5$ to 1.7, the spanwise loading suffers a strong discontinuity at the inboard and outboard flap extremities. The result is that strong trailing vortices develop along the flap side-edges as found by Crowder[20] and shown in figure 2. The resultant flow field has been examined experimentally by Radeztsky et al.[21] and computationally by Khorrami et al.[22]. The flap side-edge vortex forms close to the leading edge of the extended flap in the cove region between

---

¶Normally OASPL is measured in 1/3 octave bands. If in the lower frequency bands the 1/3 octave spectrum frequencies the spectrum is flat, this is a sign that the peak in the spectral density is at a very low frequency. This is typical of the airframe noise spectral density for the clean aircraft.

the flap and main element. The side-edge vortex is fed from the spanwise flow from the lower boundary layers, and the vortex grows in strength as it develops along the side-edge between the leading and trailing edges of the flap. The flap side-edge vortex remains close to the flap except at large flap deflections when flow separation occurs. The experimental and computational data show the side-edge vortex has a large curved feeding sheet and a near circular core.

The concept of the clean aircraft at high lift idealizes the aircraft high-lift system as able to attain lift coefficients in the approach of $\bar{C}_L = 1.5$ to 1.7 while the aircraft remains aerodynamically clean with no part-span vortices. However, noise reduction devices have to be applied so that all the excess noise of the high-lift system, including undercarriage noise, are eliminated. Such an aircraft, having a wing of large aspect ratio, would experience tip vortices. However, previous work of Brooks and Hodgson[5] suggests the increase in noise from the wing tip vortices for a wing of high aspect ratio in the high-lift configuration over that of the noise from the clean airplane at the lower lift coefficient is relatively unimportant.

We speculate that the clean aircraft at high lift has an increase in airframe noise due to the change in its upper surface boundary layer characteristics approaching the trailing edge arising from the increase in $\bar{C}_L$. We assume the noise on this clean aircraft arises exactly as with the case of the aircraft flying at lower $\bar{C}_L$, with the dominant noise being due to trailing edge scattering. Therefore, we determined the dependence of the turbulent kinetic energy and length scale in the boundary layer approaching the trailing edge as a function of the lift coefficient. Steady RANS calculations of a NACA 4412 have been performed at incidences ranging from zero to stall. The computational code CFL3D[23] was used to calculate the flows. The results show that $((u_0/V_\infty)^5 (\delta/y_m))_{\mathrm{TE}}$ increases with lift coefficient and is given approximately by

$$((u_0/V_\infty)^5 (\delta/y_m))_{TE} = \left(1 + \frac{1}{4}\bar{C}_L^2\right)^4 . \tag{10}$$

For high lift, the length scale of the energy containing eddies is given by y_m because we can no longer assume that δ_1 is a reasonable value. The actual length scale was obtained from the RANS computations of the NACA 4412 airfoil at high lift. Thus, the OASPL of the clean aircraft at high lift can be determined as follows. We first find the flight speed V corresponding to $\bar{C}_L = 0.5$. Next we determine the aircraft wing loading and the value of F. For the given aircraft, value of e will be known. Hence, its OASPL as a function of F can be calculated from

$$I(Watts/m^2) = \frac{1.7}{\pi^3}\frac{V_\infty M_\infty^2 W}{\bar{C}_L H^2}\left(1 + \frac{1}{4}\bar{C}_L^2\right)^4 = \frac{1.7}{\pi^3}F\left(1 + \frac{1}{4}\bar{C}_L^2\right)^4 \tag{11}$$

Additional detail on the justification for using such a simple formula to approximate the noise during high lift can be found in appendix A.

5.4 Comparison With Full-Scale Flight Measurements

The simple formulae for the *lower bound* of airframe noise given previously may not be sufficiently accurate for prediction purposes and the requirements of noise certification. However, it gives some insight into the dominant noise characteristics generated by a complete aircraft and its components flying in the high-lift clean configuration under conditions where all excess noise due to to the high-lift system has been eliminated.

Comparison of flight data for the clean aircraft with the trailing edge noise scattering formula show all aircraft obey the law $I \sim WV_\infty^3$, and the inverse square law H^{-2}. Such a law provides information on the *lower bound* of airframe noise for present-day types of aircraft, assuming we could entirely eliminate all extra noise arising from the dirty configuration. (We have ignored the effect of atmospheric sound absorption at the higher frequencies due to the relatively short distances involved when the aircraft is on the final approach.)

Figure 3 shows OASPL and the parameter $WV_\infty M_\infty^2/\bar{C}_L$ covering an enormous range of aircraft weights. For the clean aircraft, the agreement with experimental observations is very good. Figure 4 shows the *lower bound* curve for pre-1980 aircraft flying at various values of $(\bar{C}_L)$ on the approach at the speed V. For each aircraft of given weight W, we find a unique curve covering all values of $(\bar{C}_L) > 0.5$ using equation (11). Two example aircraft (with specific values of WMV^2/C_L at $C_L = 0.5$) are used to generate curves for $C_L > 0.5$. Figure 5 shows the *lower bound* curve for post-1980 aircraft flying at various values of $(\bar{C}_L)$ on the approach. The
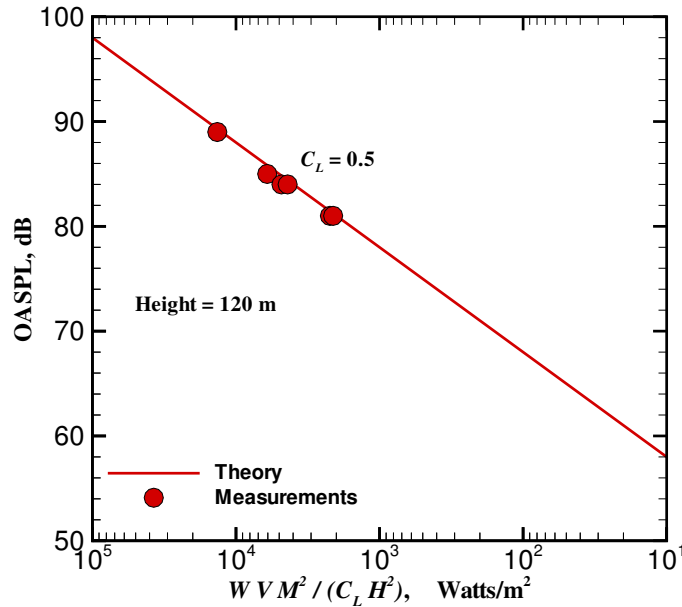
Figure 3: Theoretical and measured OASPL levels for post-1980 aircraft in a clean configuration; $H = 120$ m and $\bar{C}_L = 0.5$.

figure gives only one curve that relates to an aircraft having the all-up weight of the $B777 - 200$. It shows the difference $\Delta(dB)$ for the OASPL of this aircraft above the *lower bound* curve is about 8 dB. To obtain further noise reduction, trailing edge scattering must be addressed.

6   Trailing-Edge Scattering

If all three components of the high-lift system were eliminated on an airplane retrofitted with an advanced concept Pratt & Whitney engine, the total noise reduction during landing would be about 7 dB. It has been shown in section 5.2 that the *lower bound* for such an aircraft would be around 8 dB below that of a conventional large quad on approach. In order to reach the 10 dB goal, the noise from the clean airplane would have to be decreased. Presently, experimental and theoretical evidence suggests that the noise of the clean airplane arises from the scattering of energy in turbulent eddies in the boundary layer as they cross the wing trailing edge. Additional noise is generated at the trailing edges of all control surfaces. A detailed discussion of scattering in section 5.1 shows that the noise generated by scattering is proportional to V^5 where V is the aircraft speed. This fifth power law has been observed experimentally for all gliders, aircraft flying clean, and all birds, with the exception of the owl. The noise source suppressed on the owl is trailing-edge scattering. Thus, to reduce the noise below its lower bound requires that trailing-edge scattering be eliminated. If this could be achieved, the total aircraft noise would be proportional to V^6 with a corresponding noise reduction of almost 7 dB at approach speeds. However, other noise sources that are currently buried by high-lift noise and scattering are likely to be exposed minimizing the gains. Hence, only a few decibels of additional noise reduction may actually be realized. Nonetheless, it is likely that the 10 dB goal could be met. Many suggestions have been made regarding methods to reduce the noise from the clean aircraft, but none may be capable of developing sufficient lift during take-off and landing while not adversely affecting cruise performance.

The scattering phenomena can be interrupted by introducing a pressure release mechanism such as porous surfaces or a brush-like fringe as found on the trailing edge of owl feathers. When turbulent eddies pass over such a region that gradually transitions from the loaded wing to freestream conditions, the energy transferred to noise is
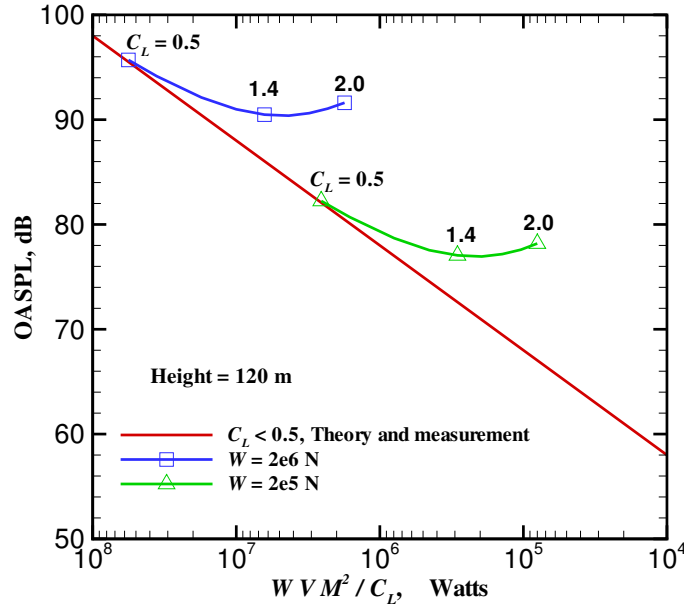
Figure 4: *Lower bound* for clean pre-1980 aircraft flying at the approach $\bar{C}_L$; $H = 120$ m and $\bar{C}_L = 0.5$.

minimal. Changes in trailing-edge geometry such as serrations have also been investigated analytically and shown to have a significant effect on the radiated noise. Other suggestions to effect scattering involve compliant surfaces and water or aerosol injection to reduce the intensity of the turbulence in the boundary layer. The complete elimination of the turbulence is the goal of laminar flow control techniques. However, conventional high-lift systems have large pressure gradients that make it very difficult to achieve laminar flow. The boundary layers will almost certainly be turbulent near the trailing edge unless the design of the airplane is significantly changed.

As the primary sources of airframe noise are eliminated, other noise sources will become the limiting factor in noise reduction. The technology that is currently being developed should provide substantial noise reduction for the high-lift system, but little is currently being done to develop methods for the other noise sources. The trailing-edge scattering mechanism is a major source of airframe noise that may become dominant with projected reductions in the noise from the high-lift system. Nature has provided us with a model to address trailing-edge scattering. The owl has three devices that help it almost eliminate scattering. The leading edge comb produces a streamwise lattice of vortices that allow the flow to remain attached over its wings even when at angles of attack that would normally produce stalling. The owl also has a fluffy down covering its wings that act as a compliant surface that damps out turbulent fluctuations. Finally, it has a fringe at the trailing edge that equalizes the pressure and prevents separation. Hardware that has the same effect but is amenable to modern aircraft is needed. In this section, we speculate on some practical ways in which owl technology could be applied to modern aircraft.

Various schemes have been proposed that have been in line with the mechanisms uncovered regarding the silent flight of the owl. The airflow over the wing of the owl is complex because not only is it at low Reynolds numbers, but the owl flies at a low speed and a high $\bar{C}_L$. For a comparable continuous wood or metal surface, the wing would stall before a lift coefficient of near unity could be attained. The flow would suffer laminar separation at the leading edge and would remain separated over the whole of the wing upper surface. The owl uses a 'comb' on the leading edge flight feathers as vortex generators to produce closely spaced streamwise vortices that form a pseudo-turbulent boundary layer with no laminar separation. However, the adverse pressure gradient near the upper surface trailing edge should still lead to boundary layer separation, a loss of lift, and result in unsteady flow leading to unsteady flight. The owl prevents this from happening by using a simple rule in fluid dynamics; 'If a flow past or over a surface is causing an unsteady flow to develop, it is worth trying to get rid of the problem by
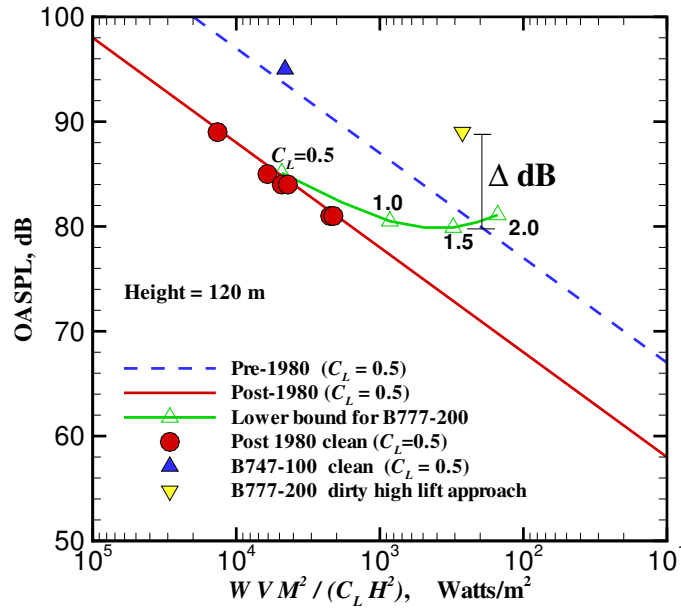
Figure 5: *Lower bound* for clean post-1980 aircraft flying at approach $\bar{C}_L$; $H = 120$ m.

eliminating the surface.' The owl has a fringe in the feathers close to the trailing edge enabling the relatively high energy lower surface boundary layer air to flow upward into the low energy upper surface boundary layer flow. This latter flow is re energized and separation is avoided. Furthermore, the fringe causes a pressure equalization between the upper and lower surfaces, and the previous large accelerations of convected eddies in the boundary layers close to the leading edge are eliminated. Thus, the owl wing achieves a high lift coefficient at low Reynolds numbers, and the flow remains steady for low speed flight. A byproduct is that there is no longer a continuous trailing edge on the owl's feathered wing and acoustic scattering proportional to M^5 has been eliminated. The loss of lift due to the reduction in available surface area, since the 'fringe' area cannot support lift, may be relatively unimportant in the case of the owl. The radiated noise is now proportional to M_∞^6, which represents a large noise reduction. For a typical aircraft approach velocity of 68 m/s the noise reduction would be of the order 7 dB. Of course, a fringe similar to that on owl's feathers would be impractical. A scheme involving porous holes close to the trailing edge has related properties to the owl's fringe. Nonetheless, the trailing edge remains, and less noise reduction would be obtained. Ornithologists have frequently drawn attention to the bird's feathers having this advantage over a solid wing surface by allowing airflow from the under surface to flow through the feathers and so help to re-energize the upper surface boundary layer by natural means. The amount of airflow on most birds is too small to produce any worthwhile effect. In the case of the owl's fringe, it is clear the effect on maintaining both high lift and steady flow has been achieved. The use of wings with porous surfaces close to the trailing edge enables an optimum scheme of natural re-energization to be employed on actual aircraft. However, a penalty may be experienced if the holes remain uncovered during cruise. An adaptive porosity scheme might prove useful.

A further scheme proposed by Fink[24][25] involves serrating the trailing edge and takes advantage of noise reduction when a trailing edge is swept with respect to the freestream direction. The noise is reduced, as shown by Howe[4], by the cube of the cosine of the trailing edge angle of sweepback. This would amount to an elimination of trailing edge noise when the angle of sweepback equals $90°$, an example for which is the owl's fringe. Of course, this does not reduce the noise to zero. Strictly speaking, the owl is never silent except to its prey who can only hear frequencies greater than $2kHz$. All flying vehicles, including all other birds apart from the owl, have a broadband spectrum extending to well beyond $10kHz$.

7   Conclusions

This study on the prediction of airframe noise concludes that only through advances in both noise reduction technology and aircraft operations will it be possible to meet the NASA goal of 10 dB noise reduction within 10 years. Major research studies are also needed to develop accurate prediction schemes that are valid for the new technology being developed. Designers will need to evaluate retrofits and completely new designs from a noise perspective as they simultaneously evaluate performance characteristics. The primary driver of the airline industry is still economics, so it is imperative that new noise reduction technology does not adversely affect cruise performance nor increase operating and maintenance costs. All of these different aspects must be investigated, and new tools need to be developed to allow the designer to perform these studies. Current research and development appears to be addressing all of these important areas, so we are optimistic that the 10 dB goal can be met.

The prediction of airframe noise depends on the availability of a space/time accurate unsteady flow database for the flow over the complete aircraft. The interactions between the component flows, such as between the undercarriage and the flap, cannot be ignored. Measurement and theory strongly point to the flow over the upper surface of the wing approaching the wing trailing edge as a dominant source of noise when the aircraft is flying in its clean configuration with flaps, slats, and undercarriage stowed. In this configuration, the estimation of airframe noise and its variation with aircraft all-up-weight and speed is well predicted by the simple formula for the turbulent boundary layer noise scattered by the wing trailing edge. The noise radiated varies with flight speed according to V_∞^5.

For aircraft flying in the dirty configuration, the radiated noise is highly geometry-dependent, but still is nearly proportional to V_∞^5. The extra noise is due to deployment of the trailing-edge flaps, the leading-edge slats, and the undercarriage. For the trailing-edge flaps, the same generic formula for edge scattering can be used although the scattering now takes place at both the flap side edges as well as at the trailing edge. In the case of the slat, its geometry is critical and good aerodynamic performance does not necessarily lead to acceptable noise performance. The avoidance of slat tones and resonances is essential within the operational range of the slat. The undercarriage is probably the most important contributor to airframe noise in the dirty configuration and possibly the most difficult component to lower its noise level.

Various methods of reducing the noise from the high-lift system and landing gear have been discussed. Substantial gains are expected from technology that is already in development, but current estimates show that elimination of high-lift associated noise alone will not meet the goal of 10 dB in 10 years for the approach condition. The shortfall will have to be made up by either changing the flight operations or addressing trailing-edge scattering. Scattering is the dominant mechanism for a plane flying in the clean configuration. The possibility of reducing the noise of the clean aircraft have been discussed. Reference was made to to the techniques employed by the owl in producing silent flight over the range of frequencies above 2 kHz. This range of frequencies is most annoying to people when aircraft fly over communities in the final approach to an airport, and is where the important high frequency weighting is generated in calculating perceived noise levels. Already, interest is being shown in developing schemes for application to aircraft based on the same principles used by owls. Although trailing-edge scattering must be addressed, changing the flight operations appears to be the most practical way to obtain the desired noise reduction in the near term. Changing flight operations would help alleviate both airframe and engine noise. Even with the combined attack recommended in this paper, obtaining the desired noise reduction will be a significant challenge. The next section makes some suggestions on how to maximize our efforts both technically and in relation to the public.

8   Recommendations

Our ability to reduce further the aircraft noise on landing can be effected if we turn to all involved in this problem. The people living close to the airport boundaries, the airport controllers, the local and federal legislators concerned with land-use planning, the pilots flying our commercial transport aircraft, as well as the aircraft and engine designers, and our scientific community must work closely together to find the best technical and economic solution. The following suggestions are proposed to address the current community noise problem.

- The aircraft industry should make public the work done to reduce the noise of aircraft over the past 30-40

years. The public hears about the success of physicists and space scientists in their work in combating disease and exploring space that they become annoyed when told that it is impossible to land an aircraft quietly. In the past 40 years the aircraft industry has reduced aircraft noise by 30 dB that is equivalent to reducing the acoustic power to $1/1000 = 0.1\%$ of its level in the early 1960's. This enormous noise reduction in terms of acoustic power was only achieved by dedicated research throughout this period. The task required all the skills of the scientific community equal to those required to send a human into space and to land on the moon. However, this enormous reduction in noise power was achieved almost solely through changes to the propulsion system. The migration from the straight jet to the modern, large diameter front fan turbojet engine yielded enormous increases in overall efficiency and large reductions in the fuel burn for a given thrust. This change in engine design not only provided significant gains in performance, but also produced enormous reductions in aircraft noise. However, few are aware of the tremendous gains that have already been achieved in performance and noise reduction.

- An effort should be made to educate the public of the inner workings of the human ear and its logarithmic response to noise. In all branches of engineering and technology, the power required to overcome resistance is the sum of the components constituting the resistance. Power requirements are reduced by decreasing the resistance of each component. Normally, it is regarded as a major advance in engineering when power requirements are reduced by as much as 50 percent, even when greater reductions are possible. The pressure fluctuations in the air associated with the propagation and radiation of sound are also measured in these same units of Watts. However, the human ear is such a remarkable organ that a human would perceive a noise source power reduction of 50 percent as small. We measure the ear's response in terms of the logarithm of the power, by the unit called the decibel. A reduction of 50 percent of the acoustic power amounts to a reduction of just 3 dB on the logarithmic decibel scale. It is only when the ear receives a noise reduction of about 10 dB, amounting to a drop in acoustic power of 90 percent, that the hearer realizes that a significant change has been made in reducing the noise of the offending noise source.

- When a source of noise has many independent components, such as in aircraft noise, the total noise level measured in dB is the sum of the logarithms of the acoustic powers of all the components. Hence, managers, researchers, and the public needs to be aware that noise sources combine in a complicated fashion that makes it difficult to achieve large reductions in perceived noise. For example, an observer clearly hears the noise of a dominant source, but sources having a level 10 dB less than the maximum are not heard. Elimination of the dominant source would achieve a significant 10 dB of noise reduction. Noise reductions made to noise sources that have levels less than the maximum produce little or no reduction to the total noise. In contrast, two sources of equal intensity produce a combined noise that is 3 dB louder than either noise source alone. Elimination of either source alone would only net 3 dB. In the airframe noise case, multiple sources are producing noise at similar intensities. All of these sources must be reduced by commensurate levels to achieve any significant overall noise reduction.

- Unfortunately, poor land planning around airports throughout the world has encourage families to live too close to airports. Today, many communities continue to be exposed to unacceptable aircraft noise during take off and landing. It is clear that if families remain in the vicinity close to an airport, no further amount of aircraft noise reduction will fully satisfy their demands to live in a peaceful urban environment. Technically, a further noise reduction of 10 dB (equivalent to reducing the noise power by 90 percent) approaches the limit of human achievement and economic feasibility. Families living close to airports should be given the means to move to quieter areas, and the land redeveloped for industrial purposes where aircraft noise would not create any problem. This should be an urgent priority for local and federal legislation and all concerned with land-use planning. In many cases, the land could be taken over by the airport to prevent further encroachment of residential areas.

- All aircraft approaching to land should fly as high as possible when flying over residential areas. Pilots should take advantage of the lower landing weights of their aircraft and use a smaller fraction of the airport runway for landing, except in the case of an emergency. The instrument landing system (ILS) glide slope of $3°$ should have its first marker positioned at one-quarter to one-third of the way from the start of the runway. These changes would enable the pilot to fly with the undercarriage stowed at a constant altitude of

twice the present height of 120 m to the intersection with the ILS glide slope. This landing approach would reduce the noise on the ground by 10 dB for people under the flight path.

- The undercarriage should be lowered during approach between the nearest community and the airport boundary. Pilots desiring to put on extra power to land could do this in the landing trajectory beyond the nearest community and possibly within the airport boundaries. The turn-off to taxiways should be toward the end of the runway instead of near the 50 percent point as at present. This change would add some minutes to the time between aircraft landing and arrival for passenger embarkation at the terminal gate. However, it would have a significant noise benefit for those continuing to live close to the airport.

- The scientific and technical community are currently seeking methods of noise reduction to the high-lift system and undercarriage without losses in performance. These technologies will provide significant noise reduction to the present and future generations of commercial aircraft. Such noise reduction will further alleviate the noise nuisance in those communities remaining under the approach path to the airport. The aim of these methods of noise reduction is to eliminate the excess noise due to the high-lift system to reduce the noise to that of a clean airplane flying at the approach speed with the same overall lift. The challenge to reduce undercarriage noise would not be so demanding provided the undercarriage was not lowered until clear of the nearest community to the airport as discussed previously. To effect a reduction in aircraft noise on the approach to landing, it is essential to reduce all the dominant noise sources by equal amounts. Thus, because undercarriage noise is a dominant noise source in the aircraft approach noise signature at ground level, our aim should be to eliminate the noise as long as possible by delaying landing gear deployment. In addition to airframe noise reduction, a corresponding decrease is required from the engine. We expect engine noise on the approach will be decreased further by using moderate increases in bypass ratio, which continue to make the engine more efficient. Furthermore, the new technologies used for airframe noise should reduce the aircraft drag and thereby decrease the required thrust during approach, which further reduces engine noise.

- If engine technology advances to reduce engine noise significantly below current levels, then the challenge will exist to reduce the airframe noise to below its current clean level. Airframe noise currently follows a V^5 law in both the clean and dirty configurations when flying at high lift. Research on the silent flight of the owl has shown it is possible to fly according to the V^6 law that involves a potential noise reduction of about 8 dB for an aircraft flying at its approach speed. This change in the power law would be obtained if the scattering of noise from the trailing edges of wings and flaps was removed. Scattering is the dominant noise source of all flying vehicles including birds except the owl. We can build on "owl technology" by research how to reduce the noise of the clean airplane.

- Previous recommendations have not referred to the subjective side of aircraft noise. Allowance has to be made for the penalties incurred in human annoyance to high frequencies above 2 kHz, especially when the noise is tonal. This involves the perceived noise scale associated with the high frequency weighting of the noise source spectrum that mimics the response of the human ear. In all the noise reduction techniques discussed previously, attention should be paid to (1) eliminating as far as possible all tones at both low and high frequencies from the noise signature, (2) reducing all excess noise at high frequency to reduce the penalty of the high frequency weighting associated with perceived noise level, and (3) reducing the noise around the peak in the spectrum to reduce the overall sound pressure level (OASPL). These changes must be accomplished while ensuring the frequency at the spectrum peak is not increased to a higher frequency. Again we can learn from owl technology. The owl possesses a "hush kit" whereby it can fly toward its prey at low speeds and high lift, similar to an aircraft on approach to landing. However, the owl remains almost totally silent at frequencies above 2 kHz. It is a challenge to the aircraft industry and scientific community to find practical methods to employ equivalent schemes for high frequency noise elimination on an aircraft by duplicating the effects of the special devices on owl feathers. When this has been achieved, the noise of the airplane measured in OASPL would almost be equal to the perceived noise level, resulting in a noise reduction of 10 dB. However, this is the subject of ongoing research, and we cannot conclude if such research will be successful.

21

The previously mentioned methods of noise reduction center on reducing the community noise annoyance and noise nuisance in areas close to airports. The methods involve both separation in distance of people from the offending aircraft as well as adding noise reduction technology to the aircraft. Some of the proposals for noise reduction will allow retrofits to existing aircraft and incorporation into future aircraft. The proposals to separate people from the approaching aircraft need careful study, but in principle could be implemented in the short term following flight and simulator studies from which new safe flight procedures could be evaluated. The necessary legislation could be introduced, but would need approval by the international organizations such as International Civil Aviation Organization (ICAO).

The aircraft industry should widely publicize the actions they take to reduce aircraft noise. The message should be that we cannot safely fly aircraft that are completely quiet during landing, but we can reduce noise beyond what has been achieved in the past 40 years.

Appendices

A   Aircraft at High Lift

To develop the lift necessary to equal the all-up weight at low forward speeds, an aircraft uses increased camber by flaps and auxiliary airfoils, called slats. In the case of flaps, the chord may be extended. Let us consider the case of an aircraft having essentially a rectangular wing for cruise and a flap for approach and landing. The mean chord and span of the main wing are $\bar{c}$ and b, respectively. The lift increment due to a flap deflection is given by

$$\Delta C_L = a_1 \tau \eta \delta_F \tag{12}$$

where a_1 is the lift curve slope, δ_F is the flap deflection and τ and η are flap parameters that depend on the geometry of the flaps and their chord extension. The value of τ is known as the flap effectiveness factor, and η is a correction to allow for viscous effects.

The lift coefficient on the wing with the flaps retracted is

$$C_{L_0} = a_1(\alpha + \alpha_0) \tag{13}$$

where the wing lift curve slope is

$$a_1 = \frac{6}{1 + 2/AR} \tag{14}$$

and α is the wing incidence, or angle of attack. The zero-lift angle is α_0. AR is the aspect ratio of the wing.

With the wing with flaps extended but at zero deflection, the lift coefficient is $C_{L_0}(1 + S_F/S)$, where S_F is the total flap area. Consider the wing with a single flap depicted in figure 6. The span of the wing is b, and the mean chord length is given by $\bar{c}$. The flap span and chord are b_F and c_F, respectively. Using lifting line theory, the lift coefficient with the flap extended and deflected is

$$\bar{C}_L = C_{L_0}\left(1 - \frac{b_F}{b}\right) + (C_{L_0} + \Delta C_L)\frac{b_F(\bar{c} + c_F)}{b\bar{c}} = C_{L_0}\left(1 + \frac{S_F}{S}\right) + \Delta C_L\left(\frac{b_{F_1}}{b} + \frac{S_F}{S}\right) \tag{15}$$

The first term in equation 15 is the contribution from the unflapped portion of the wing operating at an average lift coefficient of C_{L_0}. The second term is the contribution from the flapped portion of the wing operating with a lift coefficient of $(C_{L_0} + \Delta C_L)$ over the area of the flap and the flapped portion of the wing. The equations have been manipulated to depend on the basic wing area in cruise $S = b\bar{c}$, and the flap area $S_F = b_F c_F$.

Now consider a wing with two flaps as shown in 7. Note that both flaps contribute to the lift on the inner section of the wing in this configuration. This allows one to take into account some of the effects of the fuselage on the lift. The overall span of the outer flaps is b_{F_2} and b_{F_1} for the inboard, where $b_F = b_{F_1} + b_{F_2}$. The overall lift coefficient for the wing with flaps is $\bar{C}_L$. The lift coefficient on the outer wing beyond the flaps is C_{L_0}. The lift increments on the inboard and outboard flaps are ΔC_{L_1} and ΔC_{L_2}, respectively. The overall lift coefficient is

$$\bar{C}_L = C_{L_0}\left(1 - \frac{b_F}{b}\right) + (C_{L_0} + \Delta C_{L_2})\frac{b_{F_2}(\bar{c} + c_{F_2})}{S} + (C_{L_0} + \Delta C_{L_2} + \Delta C_{L_1})\frac{b_{F_1}(\bar{c} + c_{F_1})}{S} =$$
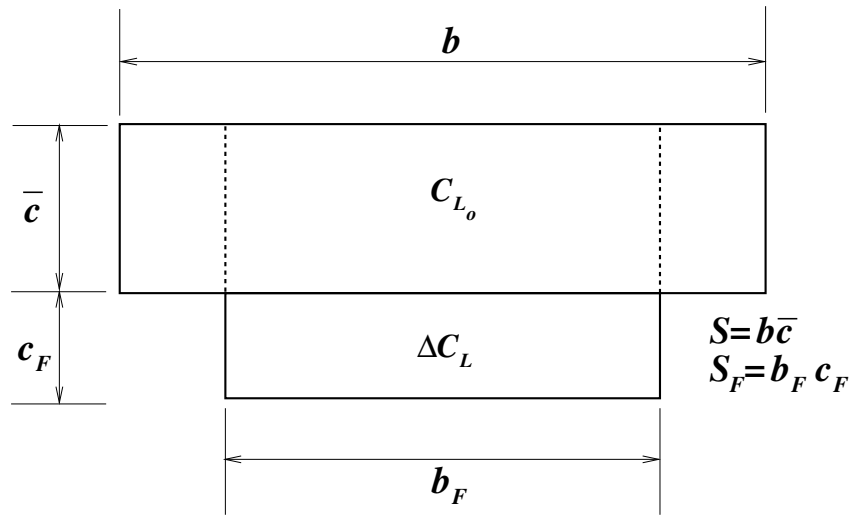
Figure 6: Schematic of a wing-flap system.
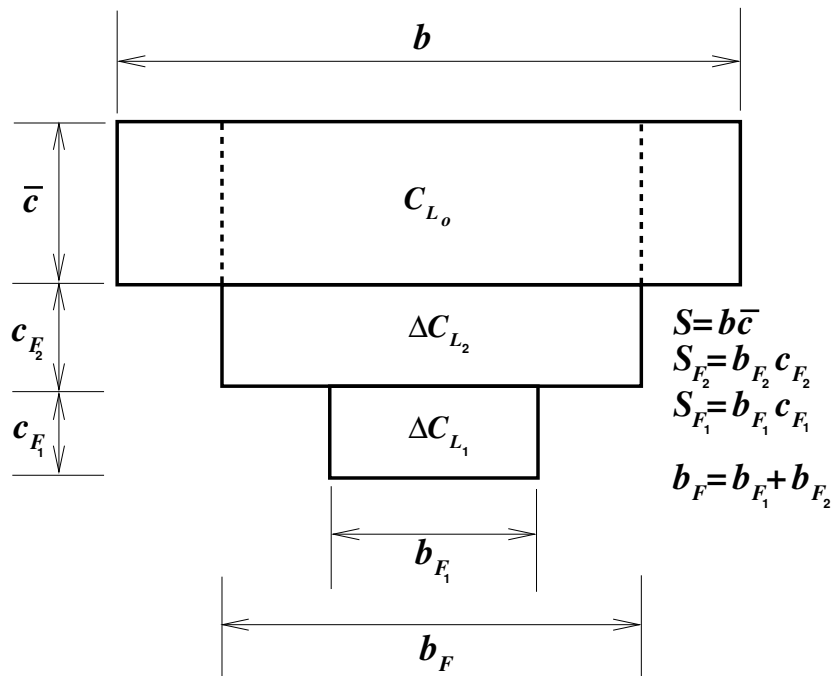
Figure 7: Schematic of a wing system with two flaps.

$$C_{L_0}(1 + \frac{S_F}{S}) + \Delta C_{L_2}\left(\frac{b_F}{b} + \frac{S_F}{S}\right) + \Delta C_{L_1}\left(\frac{b_{F_1}}{b} + \frac{S_{F_1}}{S}\right) \qquad (16)$$

where the total flap area is $S_F = S_{F_1} + S_{F_2}$.
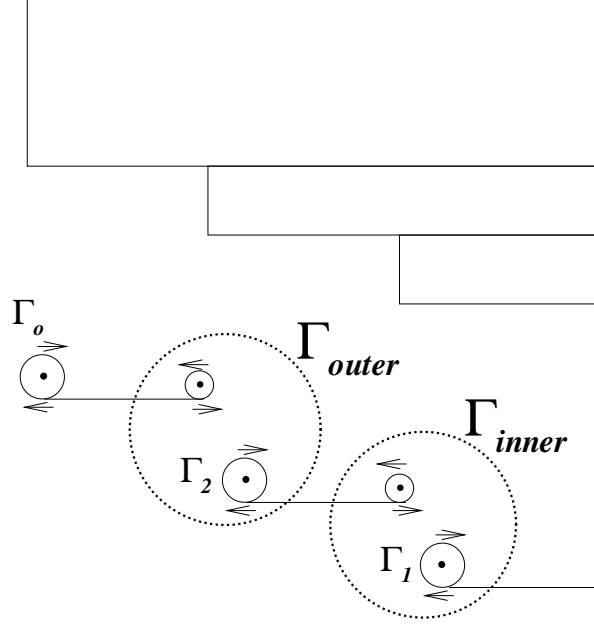
Figure 8: Schematic of the vortex system behind a wing with two flaps. Only the left half of the wing is shown.

It is also important to know the strength of the circulation around the wing. The circulation of the tip vortex is approximately given by

$$\Gamma_0 = \frac{1}{2}V_\infty \bar{c} C_{L_0} \qquad (17)$$

as in the unflapped case. The aircraft speed is V_∞. Using the experimental results for the vorticity behind a wing in figure 2 as guidance, we model the vortex system behind the wing with two flaps as shown in figure 8. The straight lines between the vortices represent vortex sheets. Clearly, we have made some approximations in assuming that the strengths of the vortices at the ends of each sheet are identical. The circulation due to the outboard flap can be determined from the difference between the strengths of the two vortices formed near the outer flap edge. Hence, the circulation at this outer edge is

$$\Gamma_{\text{outer}} = \Gamma_2 - \Gamma_0 \qquad (18)$$

Similarly, the circulation around the inboard flap edge is

$$\Gamma_{\text{inner}} = \Gamma_1 - \Gamma_2 \qquad (19)$$

where

$$\Gamma_1 = \frac{V_\infty}{2}\frac{\Delta C_{L_1} S}{b_{F_1}}\left(\frac{b_{F_1}}{b} + \frac{S_{F_1}}{S}\right) \qquad (20)$$

and

$$\Gamma_2 = \frac{V_\infty}{2}\frac{\Delta C_{L_2} S}{b_F}\left(\frac{b_F}{b} + \frac{S_F}{S}\right) \qquad (21)$$

24

Note that Γ_2 depends on the total flapped wing chord.

Because $\bar{C}_L, \Delta C_{L_1}, C_{L_2}$ are known, we can find C_{L_0}. The flight speed is V_∞, so

$$W = \frac{1}{2}\rho_\infty V_\infty^2 S \bar{C}_L \tag{22}$$

Lilley[8] reports that the turbulent flap side-edge vortex and its curved feeding sheet remain close to the flap side-edge during its evolution. It forms initially close to the flap leading edge and leaves the flap close to the flap trailing edge, where the vortex is cast off into the wake. The noise scattered at the flap side-edge depends on the flap geometry, including its number of separate elements. Double and triple slotted flaps will have different noise characteristics. The noise depends on the aerodynamic loading on each of the elements as well as the growth of the vortex along the flap side-edge. The resultant cloud of vorticity and its corresponding turbulent intensity and length scales will be functions of the change in strength of the vortex and its feeding sheet along the flap side-edge. The strength of the vortex depends on both the axial and swirl velocity components. It appears that the wing tip vortex is much weaker than the flap side-edge vortices, and the latter makes a strong contribution to the radiated noise at large incidences and correspondingly large overall lift coefficients, $\bar{C}_L$.

As shown in the previous analysis, the strength of the flap-side vortices depends on the discontinuities in the combined wing and flap geometry and the flap deflection. In other words, the strength of these vortices is dependent on the changes in the spanwise loading and is reduced when the gradients are small. Overall, the vortices must contain the same circulation regardless of the gradient of the spanwise loading. However, when the cloud of vorticity has its concentration reduced, the corresponding turbulent intensity is diminished. This condition causes a large reduction in the amplitude of the turbulent fluctuations and, hence, of the radiated noise. This description is an oversimplified model of the source of noise generated by the flap side-edge vortices. However, it gives us a clue into how to reduce this noise: we should carefully adjust the geometry of the wing-flap system so that no discontinuities in spanwise loading occur. This is the objective of the continuous mold-line link (CML) approach. A further benefit of the simple model is that once the source of the flap side-edge vortex is removed, we are left with a wing and extended flap system at high incidence that continues to radiate noise from its trailing edge, similar to the mechanism at lower incidences. Thus, our formulation can be used for the radiated noise from the wing and flap system at high lift as if it were part of the mechanism of the noise from the clean airplane. This level again acts as a lower bound for noise unless we can reduce the basic noise of the airplane at all incidences and lift coefficients. This reduction can only be achieved if we can reduce trailing edge noise.

References

[1] Fink, M. R.: Airframe Noise Prediction. FAA-RD 77-29, 1977.

[2] Crighton, D. G.: *Airframe Noise - in Aeroacoustics of Flight Vehicles: Theory And Practice*, Acoustical Society Of America, vol. 1, chap. 7. 1991. Ed. Hubbard, H.

[3] Ffowcs Williams, J. E.; and Hall, L. H.: Aerodynamic Sound Generation by Turbulent Flow in the Vicinity of a Scattering Half Plane. *Journal of Fluid Mechanics*, vol. 40, 1970, pp. 657–670.

[4] Howe, M. S.: A Review of the Theory of Trailing Edge Noise. *Journal of Sound and Vibration*, vol. 61, no. 3, 1978, pp. 437–465.

[5] Brooks, T. F.; and Hodgson, T. H.: Trailing edge noise prediction using measured surface pressures. *Journal of Sound and Vibration*, vol. 78, no. 1, 1981, pp. 69–117.

[6] Kroeger, R. A.; Gruska, H. D.; and Helvey, T. C.: Low speed aerodynamics for ultra-quiet flight. AFFDL TR 971-75, 1971.

[7] Lilley, G. M.: A study of the silent flight of the owl. AIAA 98-2340, 1998.

[8] Lilley, G. M.: The Prediction of Airframe Noise and Comparison with Experiment. *Journal Of Sound And Vibration*, vol. 239, no. 4, 2001, pp. 849–859.

[9] Grantham, W. D.; Smith, P. M.; Neely, W. R. J.; Deal, P. L.; and Yenni, K. R.: Ground-based and in-flight simulator studies of flight characteristics of a twin-fuselage passenger transport airplane during approach and landing. NASA/TP-1991-2451, 1991.

[10] Rackl, R.; Miller, G.; Guo, Y.; and Yamamoto, K.: Airframe Noise Studies - Review and Future Direction. NASA Contract NAS 1-97040, The Boeing Company, 2001.

[11] Powell, A.: Aerodynamic noise and the plane boundary. *Journal of the Acoustical Society of America*, vol. 32, 1960, pp. 982–990.

[12] Crighton, D. G.: Radiation from vortex filament motion near a half plane. *Journal of Fluid Mechanics*, vol. 51, no. 2, 1972, pp. 357–362.

[13] Goldstein, M. E.: *Aeroacoustics*. McGraw-Hill Book Company, New York, 1976.

[14] Howe, M. S.: *Acoustics of fluid-structure interactions*. CUP, New York, 1998.

[15] Crighton, D. G.; Dowling, A. P.; Ffowcs Williams, J. E.; Heckl, M.; and Leppington, F. G.: *Modern methods in analytical acoustics*, Springer-Verlag. 1992.

[16] Howe, M. S.: Noise produced by a saw-toothed trailing edge. *Journal of the Acoustical Society Of America*, vol. 90, 1991, pp. 482–487.

[17] Singer, B. A.; Lockard, D. P.; Brentner, K. S.; and Lilley, G. M.: Simulations of Acoustic Scattering from a Trailing Edge. AIAA-99-0231, Presented at the 37th Aerospace Sciences Meeting and Exhibit, Reno, NV, January, 1999.

[18] Ffowcs Williams, J. E.; and Hawkings, D. L.: Sound generated by turbulence and surfaces in arbitrary motion. *Philosophical Transactions Of The Royal Society Of London A*, vol. 264, no. 1151, 1969, pp. 321–342.

[19] Ostertag, J.; Guidati, S.; Guidati, G.; Wagner, S.; Wilde, A.; and Kalitzin, N.: Prediction and Measurement of Airframe Noise on a Generic Body. AIAA-2000-2063, Presented at the 6th AIAA/CEAS Aeroacoustics Conference, 2000.

[20] Crowder, J. P.: *Recent advances in flow visualization at Boeing Commercial Airplanes*. Hemisphere Publishing, New York, 1989. 5th International Symposium on Flow Visualization - Prague, Czechoslovakia.

[21] Radeztsky, R. A.; Singer, B. A.; and Khorrami, M. R.: Detailed measurements of a flap side-edge flow field. AIAA 98-0700, 2000.

[22] Khorrami, M. R.; Singer, B. A.; and Radeztsky, R. H., J.: Reynolds-Averaged Navier-Stokes Computations of Flap-Side-Edge Flowfield. *AIAA Journal*, vol. 37, no. 1, 1999, pp. 14–22.

[23] Biedron, R. T.; and Thomas, J. L.: A Generalized Patched-Grid Algorithm with Application to the F-18 Forebody with Actuated Control Strake. *Computing Systems in Engineering*, vol. 1, no. 2, 1990, pp. 563–576.

[24] Fink, M. R.; and Bailey, D. A.: Model tests of airframe noise reduction concepts (trailing-edge flap and leading-edge slat modifications. AIAA 80-0979, 1980.

[25] Fink, M. R.: *Propulsive Lift Noise - in Aeroacoustics of Flight Vehicles: Theory And Practice*, Acoustical Society Of America, vol. 1. 1991, pp. 449–481. Ed. Hubbard, H.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD-MM-YYYY)* 01-04-2004	2. REPORT TYPE Technical Memorandum	3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

The Airframe Noise Reduction Challenge

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

David P. Lockard and Geoffrey M. Lilley

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
23-781-10-10

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

L–18346

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)

NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

NASA/TM–2004–213013

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited
Subject Category 71
Availability: NASA CASI (301) 621-0390   Distribution: Nonstandard

13. SUPPLEMENTARY NOTES

An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://ntrs.nasa.gov.

14. ABSTRACT

The NASA goal of reducing external aircraft noise by 10 dB in the near-term presents the acoustics community with an enormous challenge. This report identifies technologies with the greatest potential to reduce airframe noise. Acoustic and aerodynamic effects will be discussed, along with the likelihood of industry accepting and implementing the different technologies. We investigate the *lower bound*, defined as noise generated by an aircraft modified with a virtual retrofit capable of eliminating all noise associated with the high lift system and landing gear. However, the airframe noise of an aircraft in this "clean" configuration would only be about 8 dB quieter on approach than current civil transports. To achieve the NASA goal of 10 dB noise reduction will require that additional noise sources be addressed. Research shows that energy in the turbulent boundary layer of a wing is scattered as it crosses trailing edge. Noise generated by scattering is the dominant noise mechanism on an aircraft flying in the clean configuration. Eliminating scattering would require changes to much of the aircraft, and practical reduction devices have yet to receive serious attention. Evidence suggests that to meet NASA goals in civil aviation noise reduction, we need to employ emerging technologies and improve landing procedures; modified landing patterns and zoning restrictions could help alleviate aircraft noise in communities close to airports.

15. SUBJECT TERMS

Aeroacoustics, Noise Reduction

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)
a. REPORT	b. ABSTRACT	c. THIS PAGE			
U	U	U	UU	31	19b. TELEPHONE NUMBER *(Include area code)* (301) 621-0390

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18